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ON THE THERMAL RADIOEMISSION OF MERCURY

by

Yu. N. Vetukhnovskaya
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ABSTRACT

Analysis of the physical conditions of the planet Mercury through radio astronomical measurements of the luminance temperature indicates the possibility of successfully investigating the temperature regime of Mercury and the thermal and electrical properties of its surface material.

Significant information about the thermal properties of the planet's surface may be obtained from measurements of the luminance temperatures of the night side of the planet in the IR portion of the spectrum. In order to interpret the results of the measurements it is necessary to establish the relation between the measured quantities and the physical properties of the surface material.

Discussed in this paper is the thermal regime and the radioemission of Mercury. A comparison is made between theory and experiment.

INTRODUCTION

In the last few years there has been a series of new experimental data on Mercury,[1] permitting the analysis of the physical conditions of this planet. Thus, radio astronomical measurements of the luminance temperatures of Mercury and the dependence of these on phases of illumination of the planet by the Sun and on the wavelength of the radioemissions employed admit a possibility, analogously to that for the Moon,[2] of investigating the temperature regime of Mercury and the determination of the thermal and electrical properties of its surface material. Significant information about the thermal properties of the planet's surface may be obtained from measurement of the luminance temperatures of the night side of the planet in the IR portion of the spectrum. In order to interpret the results of the brightness temperature measurements it is necessary to establish the relation between the measured quantities and the physical properties of the surface material. Unfortunately, the theory of radioemission of the Moon, worked out in detail by Troitski and Krotikov,[3,4] cannot

be directly applied to Mercury inasmuch as, first, the insolation of Mercury is on the average an order of magnitude greater than that for the Moon; second, because of the large eccentricity of the orbit, the insolation varies by more than a factor of two during the motion of Mercury in its orbit; and third, the duration of the solar day on Mercury is approximately six times larger than that on the Moon and exactly twice as great as the Mercurian year.

The first calculations of the thermal regime on Mercury were made by the authors,[1] Soter and Ulrichs,[5] and K. Sagan and D. Morrison.[6] The present paper further develops the theory of radioemission from Mercury.

The Thermal Regime of Mercury

In connection with the tenuous nature of the Mercurian atmosphere it is possible, in the first approximation, to neglect its influence on the temperature regime. The temperature of the surface and its distribution with depth as a function of the phase of illumination of the planet by the Sun and of the planet's heliocentric longitude has been obtained by numerical solution of the one-dimensional heat conduction equation under the assumption that the thermal properties of the material of the surface layer do not vary either with depth or temperature $\gamma = (\kappa\rho c)^{-1/2}$. Here κ is the thermal conductivity, ρ the density, and c the specific heat.

The basic results of the calculation have been graphically presented.[1] It was here assumed that the velocity of orbital motion was constant. It is known that the period of revolution of Mercury about the Sun is accurately half the duration of a solar day. For this reason the conditions of insolation periodically repeat themselves from one solar day to the next for each point of the surface, and it may be taken that the temperature of the surface at a given point turns out to be a periodic function with period $\tau = 176$ days and may be represented in the form of a Fourier series

$$T(t,y,\varphi,\psi,\gamma) = T_0 \cos^{\beta_0}\psi + \sum_{n=1}^{\infty} T_n e^{-y\sqrt{\frac{n}{2\alpha^2}\frac{2\pi}{\tau}}} \cos\left(n\frac{2\pi}{\tau}t - n\varphi - \varphi_n - y\sqrt{\frac{n}{2\alpha^2}\frac{2\pi}{\tau}}\right)\cos^{\beta_n}\psi_7 \qquad (1)$$

where T_0 is the constant component, T_n and φ_n the amplitude and phase shift of the n^{th} harmonic, φ and ψ are the planetocentric longitude and latitude, $\alpha^2 = \frac{\kappa}{\rho c}$ the coefficient of thermal diffusivity. The distribution of temperature with latitude approximates a dependence of the form

$$T_n(\psi) = T_n(O) \cos^{\beta_n} \psi \; .$$

The exponential index β_n of this approximation is determined from the solution of the heat conduction equation for $\psi = 0°, 6°, 12°, 18°, 24°, \ldots 84°$ and for $\beta_0 = 0.191$, $\beta_1 = 0.374$, $\beta_2 = 0.289$, $\beta_3 = 0.520$.

The constant component and harmonics of the surface temperature depend on the heliocentric longitude of the subsolar point of Mercury. Analysis of the calculated results show that, for the constant component and first two harmonics, this dependence may be approximated by a linear function of the heliocentric distance of Mercury $\tau_{☿}$:

$$T_n\left(\tau_{☿}\right) = T_{n0} - \Delta T_n\left(\tau_{☿} - \tau_0\right) \qquad (2)$$

where T_{n0} is the value of the constant component and harmonics for perihelion. The values T_{n0} and ΔT_n for various γ are shown in Table I. The error of the approximation is less than 1 percent.

The data presented give, in analytical form, the distribution of temperature over the surface as a function of time and heliocentric distance.

The Radioemission of Mercury

As a consequence of the fact that present-day radio telescopes have a directional beam width larger than the angular diameter of Mercury, measured values from radio astronomical observations turn out to be in general a brightness temperature as averaged over the visible disc of the planet $\overline{T}_{Я☿}$. As the phases of Mercury change, the terrestrial observer views various portions of the surface which are, as shown above, in various temperature conditions.

The period of phase change (116 days) is not a multiple of the Mercurian solar "day." Thus, the dependence of the luminance temperature of Mercury on the phase angle does not turn out to be a periodic function and hence an approximation to the observed radioluminance temperature of the functional form

$$\overline{T}_{\text{Я}☿}(\phi) = \overline{T}_{\text{Я}0} + T_{\text{Я}\sim} \cos(\phi - \chi)$$

is not admissible. The luminance temperature of Mercury depends not only on phase but also on the heliocentric distance. The radioemission of a heated body with a known surface temperature distribution and with depth, satisfying relations (1) and (2), can for given ϕ (or t) and $\tau_{☿}$ be found by integrating over the depth y and over φ and ψ analogously to those previously recorded[3, 4]:

$$\overline{T}_{\text{Я}☿}(\phi, \tau_{☿}, \gamma, \delta_1, \epsilon) = (1 - R_{\perp})\Bigg\{F_0 T_0\left(\tau_{☿}, \gamma\right) + \sum_{n=1}^{4} T_n\left(\tau_{☿}, \gamma\right) \frac{F_n}{\sqrt{1 + 2\delta_n + 2\delta_n^2}} \cos\left[n\phi + \varphi_n\left(\tau_{☿}, \gamma\right) + \xi_n\right]\Bigg\}. \quad (3)$$

Here ϵ is the dielectric constant of the surface material, $R_{\perp} = \left(\frac{\sqrt{\epsilon} - 1}{\sqrt{\epsilon} + 1}\right)^2$, $\delta_1 = \frac{\ell_3}{\ell_t}$ is the ratio of penetration depths of electromagnetic and thermal waves, F_0 and F_n are the averaging coefficients for conversion from brightness temperature at the center of the disc to the average over the disc of the luminance temperature, ξ_n is the phase shift of the n^{th} harmonic of the radio temperature in relation to the phase of the surface temperature. The totality of presented data makes it possible to calculate the averaging of the luminance temperature of Mercury over the visible disc for given $\tau_{☿}$ and ϕ under the assumptions that the electric and thermal properties of the surface material are constant and the surface is reasonably smooth when compared to a wavelength.

Comparison of Theory with Experiment

From the presently available radio astronomical observations of Mercury[7–10] there is a sufficient coverage of time intervals for the measurement of phase dependence which can give information about the thermal and electrical parameters of the surface.

For the observational period of Kaftan-Kassim and Kellerman[7] the luminance temperatures for various γ and δ_1 have been calculated by formula (3). It is assumed that $\epsilon = 2.5$.[1] The functional relations so obtained are shown in Figures 1, 2, and 3. It may be seen that for corresponding selections of δ_1 the calculated dependence $\overline{T}_{\text{Я☿}}(\phi)$ is within the limits of error in agreement with experimental data in the interval $\gamma = 250$-800.

As is known, for good dielectrics, with tangents of the dielectric loss angle $\mathrm{tg}\,\Delta \ll 1$, the relation for penetration depth of electric and thermal waves may be expressed by the formula

$$\delta_1 = \frac{c}{2\sqrt{\pi \epsilon \tau}\ \mathrm{tg}\,\Delta/\rho}\,\gamma\lambda = \alpha\lambda \tag{4}$$

where the coefficient α for silicate rock does not vary with λ in the millimeter and centimeter wavelength range. The values of α obtained from comparison with observational results at $\lambda = 1.9$ cm are shown in Table II.

Comparison with the observations of Epstein[8] at 0.34 cm cannot, unfortunately, be made in detail, inasmuch as the measured results are approximated by the relation

$$\begin{array}{llll} T_{\text{Я☿}}(\phi) = & 291 & + \ 87 \cos & (\phi + 41) \\ & \pm\ 15 & \pm\ 18 & \qquad \pm\ 13 \end{array}$$

which does not reflect the dependence of $\overline{T}_{\text{Я☿}}$ on $\tau_{☿}$.

For a mean distance of Mercury from the Sun, the corresponding observations at $\lambda = 0.34$ cm, the value of α is 1.8 for $\gamma = 100$ and $\alpha = 3$ for $\gamma = 500$ which is approximately a factor of five greater than the values determined from the observations at $\lambda = 1.9$ cm[7] (Table II). This difference is considerably in excess of previously quoted measurement errors[7,8] and attests either to the error of at least one of these measurements or the non-applicability to Mercury of the theory of thermal emission discussed above.

The results of Kellerman's measurement[9] have a rather large scatter and may be satisfied, for practical purposes, by an arbitrary value of γ (Figure 4).

Observations at $\lambda = 0.8$ cm[10] in general do not agree with the calculations for any value of γ and δ_1.

The luminance temperature $\bar{T}_{\text{Я☿}} = (450 \pm 60)\,°K$, obtained by Welch and others[11] from observations at $\lambda = 1.53$ cm during 11-15 September 1964 also do not agree with calculations for any values of γ and δ_1.

Finally, the latest measurements of luminance temperatures of the night side of Mercury made in the IR portion of the spectrum,[12] in agreement with which $T_H < 150\,°K$ corresponds to $\gamma > 100$.

The inadequacy of detailed data and the mutually reciprocal contradictions in significant portions of the experimental results contribute to a general indeterminancy and unreliability in the present state of the quantitative estimates of thermal and electrical properties of the surface materials of Mercury. Thus the interval of possible values of $\gamma = 100 - 800$ gives a scatter of two orders in the determination of the coefficient of thermal conductivity κ. The respective previous measurements[7,8] show an interval of values $\alpha = 0.15 - 3$, which leads to a range of values for tg Δ/ρ from 10^{-2} to 0.05×10^{-2}.

The range of possible values of γ, κ, and tgΔ/ρ, found above, include the values of these parameters selected for the Moon ($\gamma = 500$, $\delta_1 = 1.38 \times 10^{-3}\,\gamma\lambda$), so that the similarity of the surface parameters of the Moon and Mercury are not excluded.

TABLE I

γ	20	40	100	250	500	800
T_{00} ΔT_0	401 47.0	385 44.3	366 42.5	350.1 42.1	340.1 42.5	334 42.3
T_{10} ΔT_1	250.1 192	271.9 191.7	296.3 191.7	316.2 191.6	328.8 191.2	336.2 191.4
T_{20} ΔT_2	83.3 331.8	84.7 336.5	86.1 338.6	87.1 339	87.1 338.6	87.3 338.6

TABLE II

Observer	λ_{cm}	γ	$\alpha = \frac{\delta_1}{\lambda}$
B. Murray[12]		100	
E. E. Epstein[8]	0.34	100 150	1.8 3
V. K. Golovkov, B. Ya. Losovskiy[10]	0.8	None	
W. J. Welch[11]	1.53	None	
M. A. Kaftan-Kassim, K. I. Kellerman[7]	1.9	250 500 800	0.47 0.69 0.79
K. I. Kellerman[9]	11	Arbitrary	

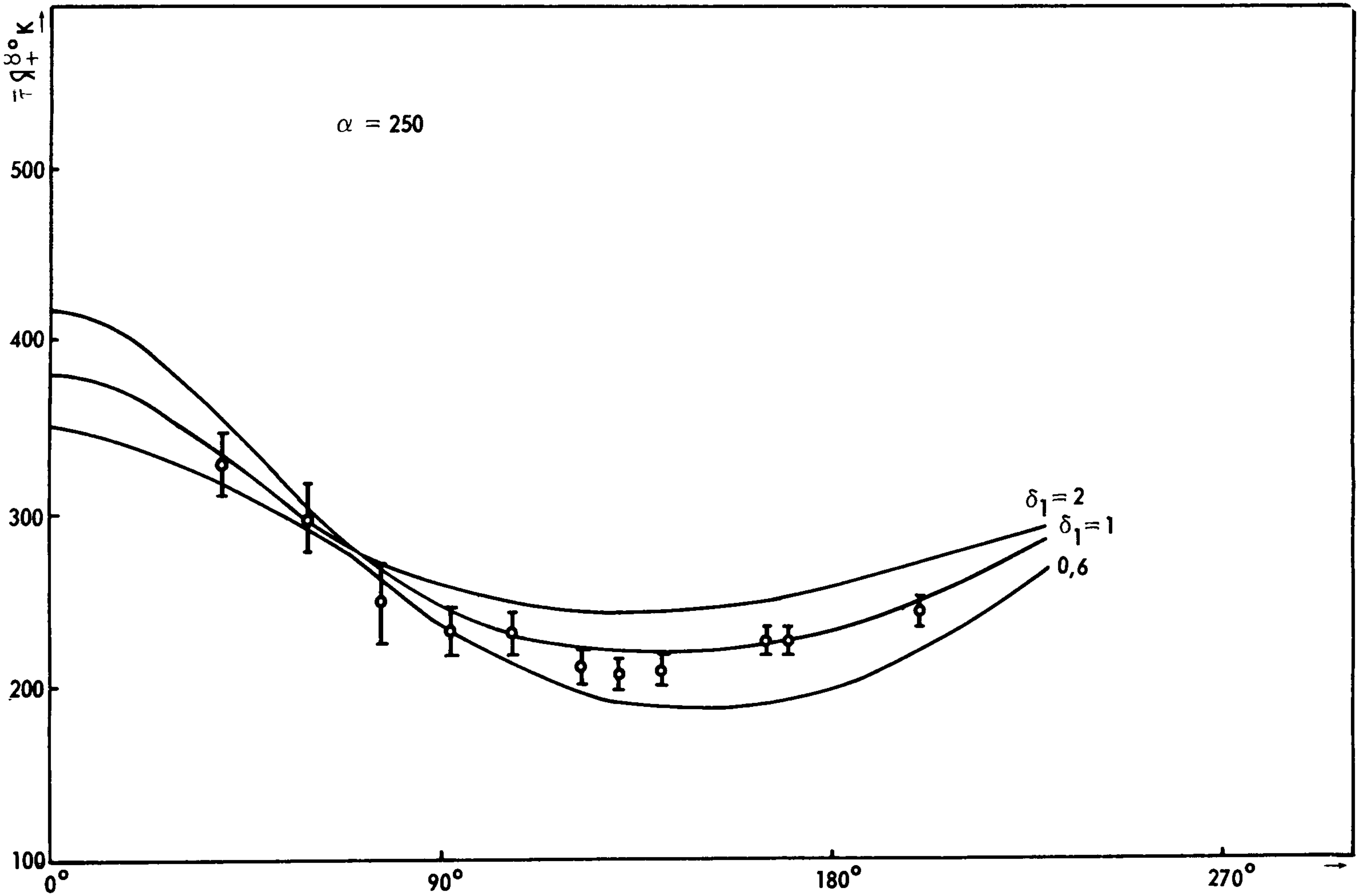

Figure 1. Phase dependence of luminance temperature of Mercury averaged over the planet's disc (for the period January–March 1966 for $\gamma = 250$ and $\delta_1 = 0.6$; 1 and 2 and measured data[7]).

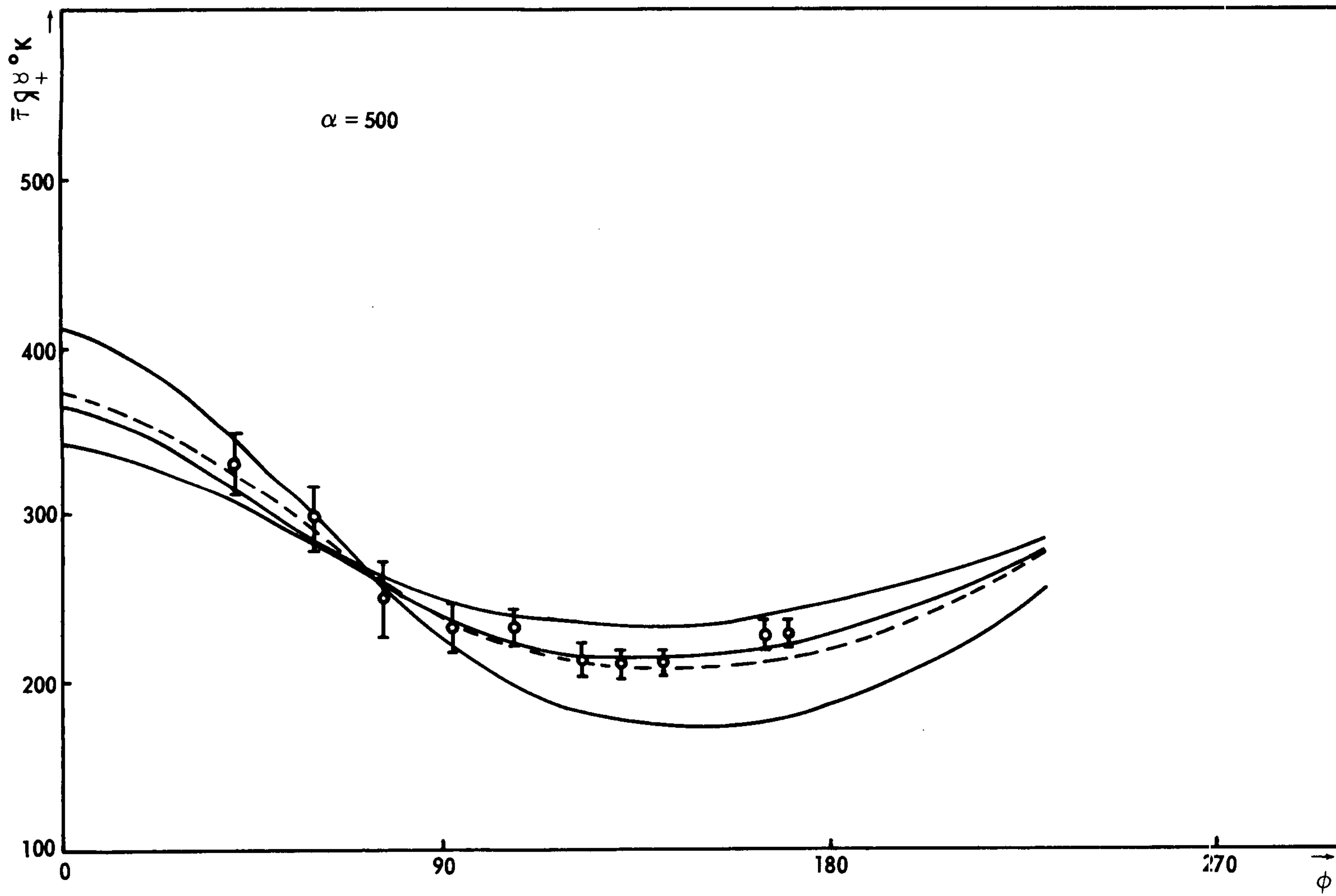

Figure 2. Phase dependence of luminance temperature of Mercury averaged over the planet's disc (for the period I-III 1966 for $\gamma = 500$ and $\delta_1 = 0.6$; 1.3 and 2 and measured data[7]).

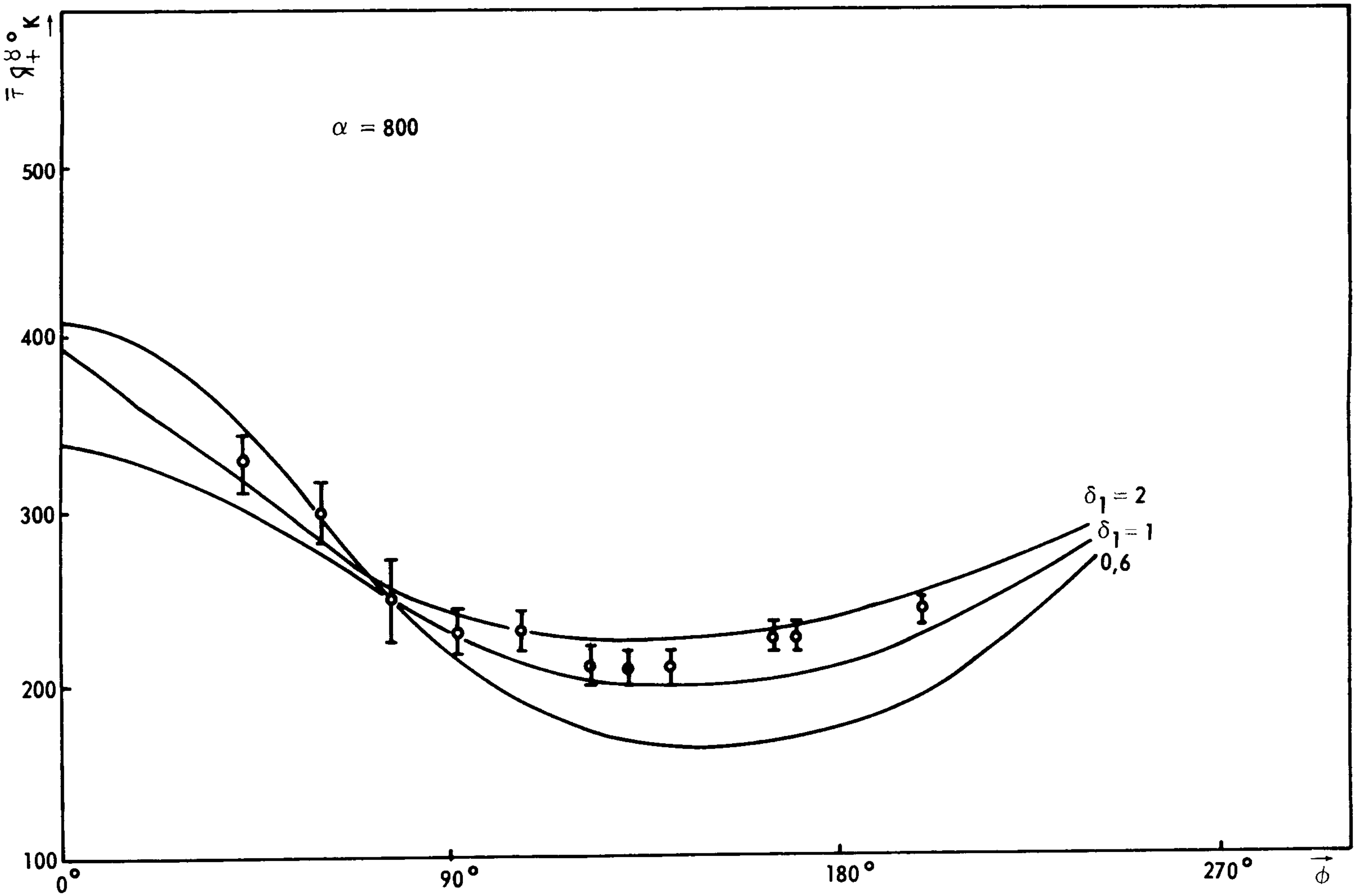

Figure 3. Phase dependence of luminance temperature of Mercury averaged over the planet's disc (for the period I-III 1966 for $\gamma = 800$ and $\delta_1 = 0.6$; 1 and 2 and measured data[7]).

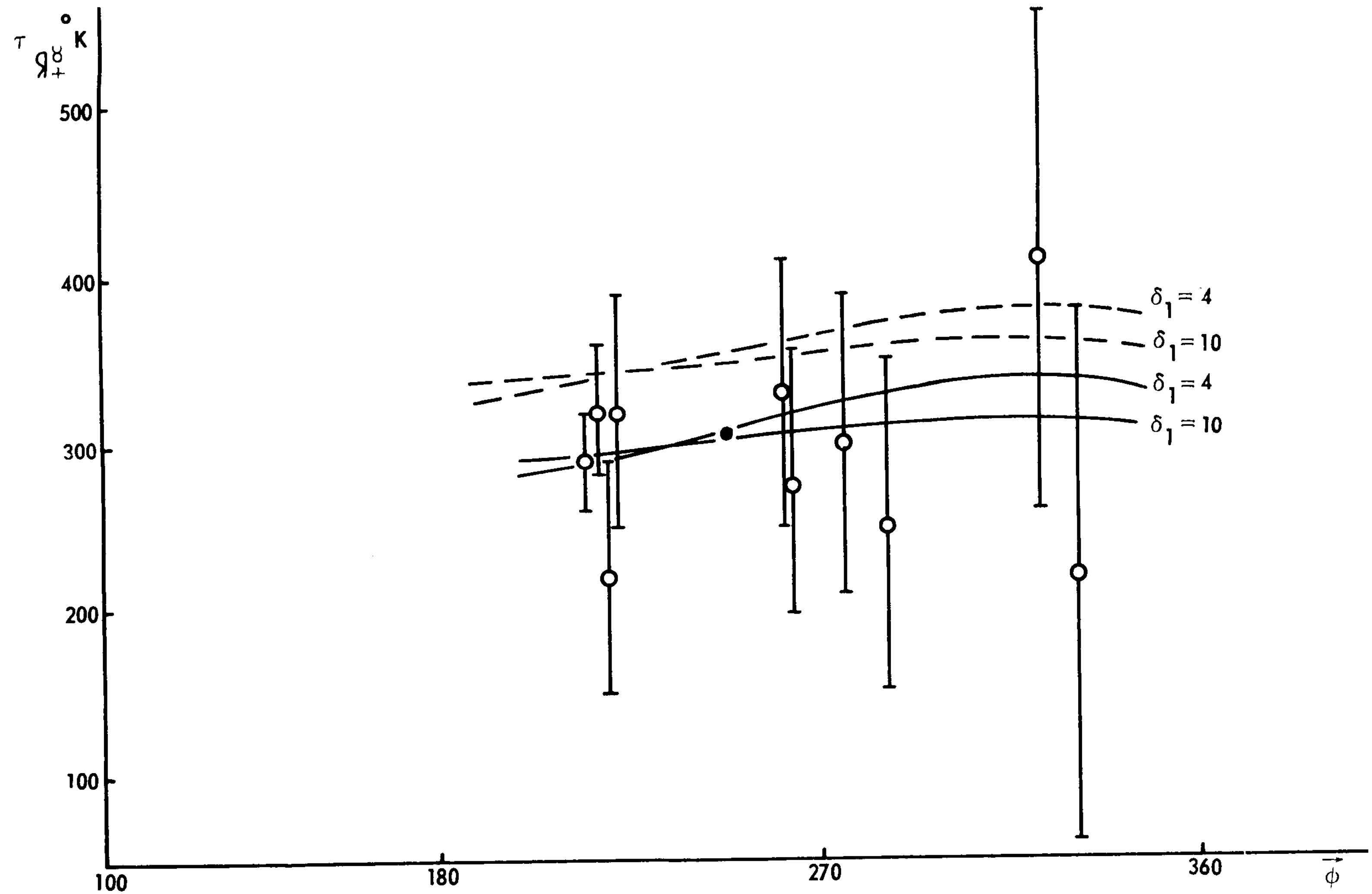

Figure 4. Phase dependence of luminance temperature of Mercury averaged over the planet's disc [for the period Y-Y1 1964 for $\gamma = 20$ (-----) and $\gamma = 500$ (-----) and experimental data[10]].

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